Design and Control of an Unmanned Aerial Vehicle for Autonomous Parcel Delivery with Transition from Vertical Take-off to Forward Flight - VertiKUL, a Quadcopter Tailsitter

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Design and Control of an Unmanned Aerial Vehicle for Autonomous Parcel Delivery with Transition from Vertical Take-off to Forward Flight - VertiKUL, a Quadcopter Tailsitter

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ABSTRACT
This paper presents the design and control of VertiKUL, a Vertical Take-Off and Landing (VTOL) transitioning tailsitter Unmanned Aerial Vehicle (UAV), capable of hover flight and forward flight for the application of parcel delivery. In contrast to existing transitioning UAVs, VertiKUL is not controlled by control surfaces, but exclusively by four propellers using differential thrust during hover flight, transition and forward flight. A numerical design method optimising range and payload is developed for initial sizing. A simulation model is implemented in Simulink to evaluate different control strategies before conducting test flights. A unique mid-level control strategy enabling intuitive control of VertiKUL which requires no pilot skills is developed. Fluent transition from hover to forward flight is achieved through an autonomous control strategy. Attitude control based on quaternions instead of Euler-angles is implemented to avoid singularities. The resulting design, VertiKUL, is built and test flown.

Index Terms: VTOL, hybrid UAV, transition, parcel delivery, tailsitter, numerical design optimisation, autonomous navigation

1. INTRODUCTION

The past years UAVs have known an increase in interest and availability. They are widely used in civil applications and areas such as agricultural observation and aerial photography. Another interesting application is parcel delivery. For this purpose VertiKUL is designed. Figure 1 shows VertiKUL in hover flight. Its main design feature is the capability of transitioning from hover flight to forward flight. Manoeuvrability of a quadcopter and efficient forward flight of a conventional airplane are combined into one transitioning UAV. For intuitive manual control of VertiKUL, a unique control strategy requiring no flying skills from the user, is developed.

There are several ways to perform transitioning manoeuvres: thrust-vectoring, tilting-rotor, tilting-wing, etc. Famous transitioning manned vehicles using thrust-vectoring and tilting- rotor are Harrier and V-22 Osprey respectively. Examples of unmanned tilt-rotor vehicles are Wingcopter [1] and FireFLY 6 [2]. These concepts involve significant extra mechanical complexity which increases cost, maintenance and risk of failure. The explicit choice is made to avoid the use of such tilting mechanisms. This means VertiKUL purely relies on differential thrust created by the four propellers to perform a transition and to control the UAV in both hover and forward flight. This concept can be regarded as tilting- body. Other examples of unmanned vehicles that transition using differential thrust only are Quadshot [3] and ATMOS UAV [4]. However, these UAVs still have

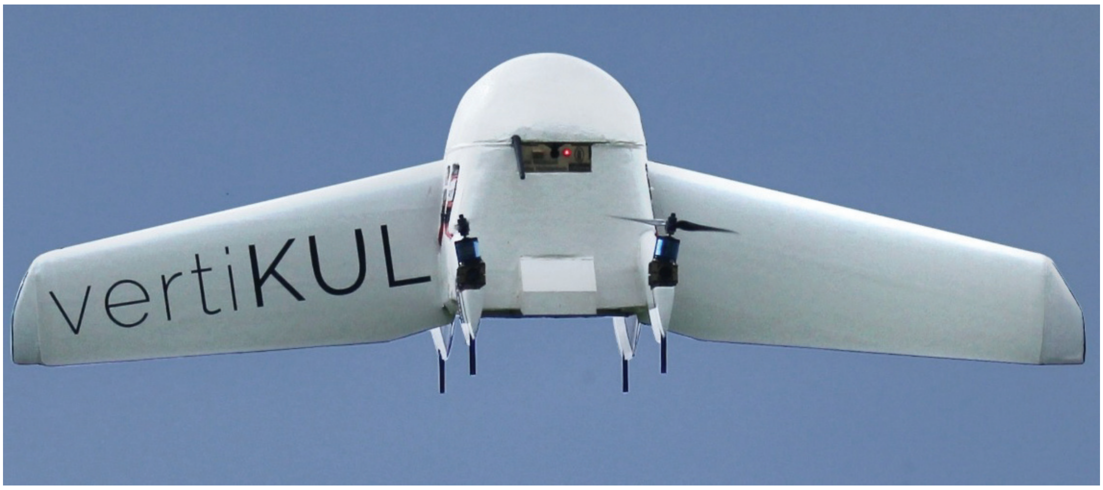


Figure 1: VertiKUL UAV during hover flight

tilting rotors or actuated control surfaces to control the vehicle in level flight. With respect to the absence of additional actuators few similar projects were found in literature. One is being researched by V. Hrishikeshavan et al at the University of Maryland University in the United States [5], another one is being researched by A. Oosedo et al at the Tohoku University in Japan [6].

2. DESIGN OF VERTIKUL VTOL UAV

VertiKUL has a unique fixed wing quadcopter hybrid design, capable of both VTOL and efficient forward flight. The design has the major innovation of having no additional control surfaces for attitude control and stability. This greatly reduces cost, maintenance and risk of failure. VertiKUL is capable of transporting a payload up to 1 kg and is optimised for range. In the design process of the VertiKUL, an initial configuration that complies best with the requirements is designed. Next, initial sizing is done using a numerical approach optimising the range. After analysing, the proposed solution is designed in detail. Finally, tests with several prototypes are done to confirm the analyses and design.

2.1 Configuration

VertiKUL has a fixed low wing configuration. Four fixed-pitch propellers provide lift during hover flight and thrust during level flight. They also provide attitude control by exerting moments on the frame using differential thrust. The payload is placed at the center of gravity of VertiKUL to ensure the same flight characteristics for all payload masses.

Figure 2 shows the following design features:

- Fixed low wing tailsitter design
- Passive wing without control surfaces reducing complexity
- Four fixed-pitch propellers
- High capacity rechargeable lithium polymer batteries for long range
- Rear-end opening for payload insertion
- Winglets for directional stability and reduced drag during forward flight

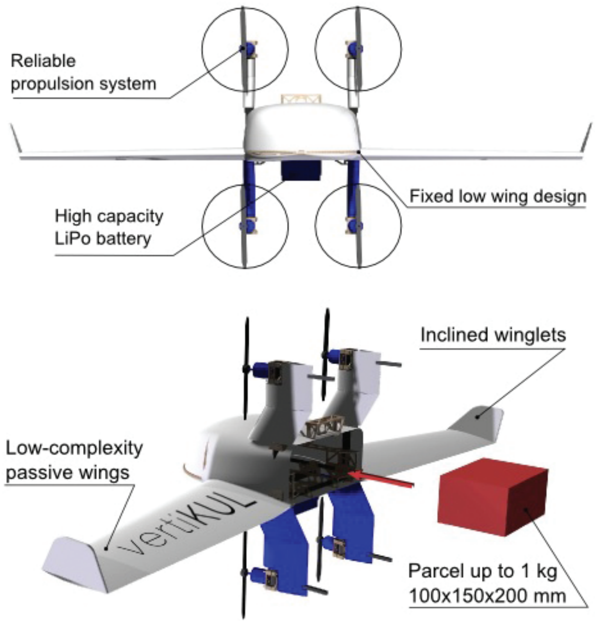


Figure 2: VertiKUL design features.

2.2 Numerical design optimisation

In the numerical design optimisation, range is maximized with given constraints. The range of an electric propeller-driven aircraft can be expressed as [7]:

$$R = \underbrace{\frac{k_{bat}}{g}\, mf_{bat}}_{\text{battery}} \cdot \underbrace{\frac{C_L}{C_D}}_{\text{aerodynamics}} \cdot \underbrace{\eta_{propulsion}}_{\text{technology level}} \tag{1}$$

k_{bat}: gravimetric energy density battery [J/kg]
mf_{bat}: mass fraction battery [-]
C_L/C_D: aerodynamic efficiency [-]
$\eta_{propulsion}$: propulsion group efficiency (ESC, motor, propeller) [-]

Range is maximized when flying at maximum lift to drag ratio. This occurs at minimum drag speed.

VertiKUL is designed following a numerical method written in Matlab. The proposed method combines models and databases of components and selects the best solution taking all constraints into account. Figure 3 shows the general design approach. The filtered solution set is shown in figure 4.

The best solution for 1 kg payload forms the starting point for the detailed design of VertiKUL which is described in section 4.

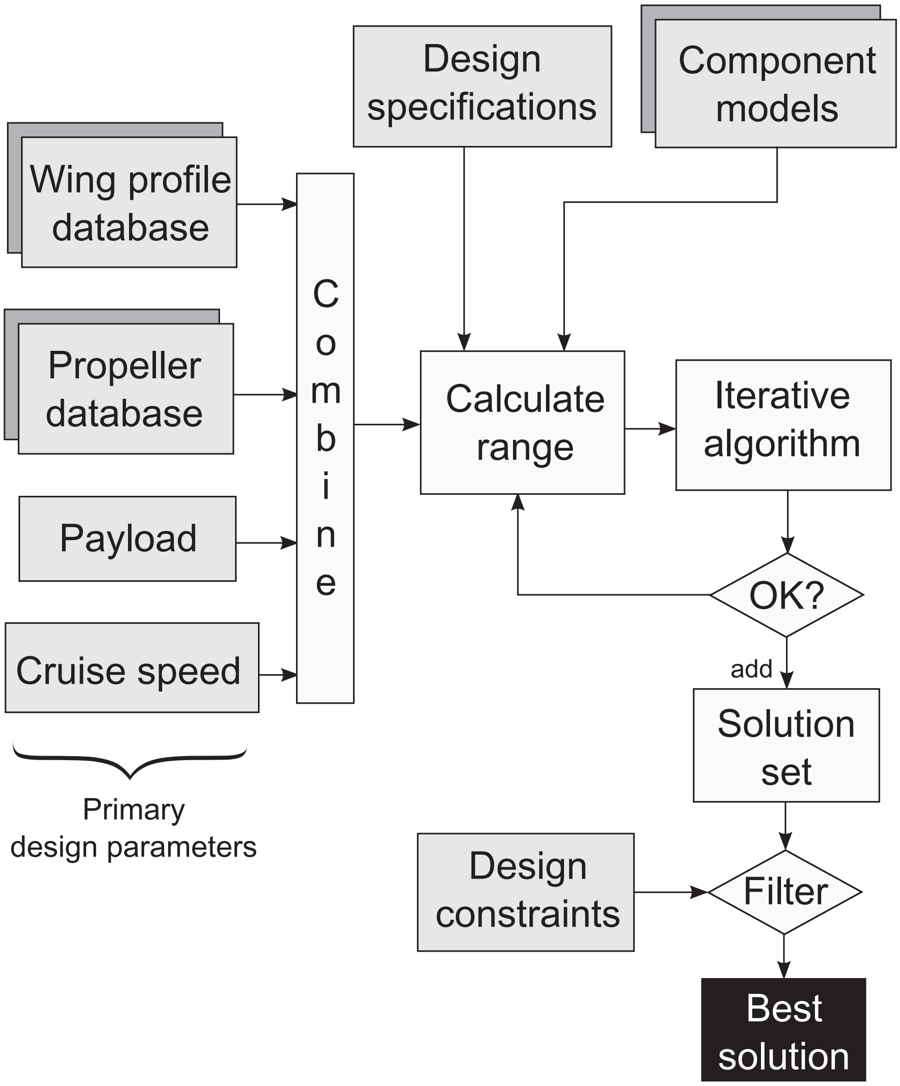


Figure 3: Design optimisation approach.

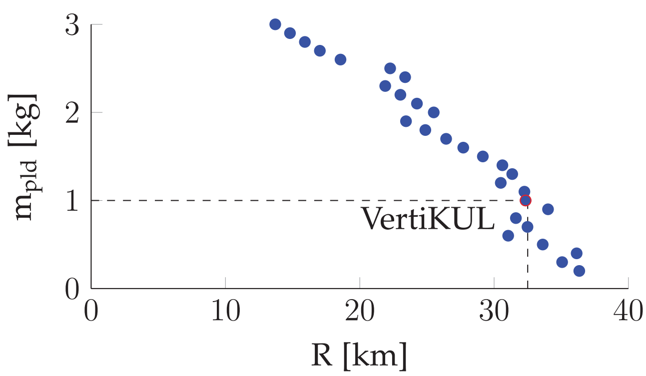


Figure 4: Filtered solution set showing the best solutions for different payloads.

3. CONTROL

VertiKUL can be controlled in a low-level and mid-level mode which provide acrobatic and intuitive flight capabilities respectively. The high level mode for autonomous flight was not yet implemented. Each mode has its own controller with reference generator, translating user input into reference signals. The reference generator and controller are designed and simulated using the Simulink program and are implemented on a Pixhawk autopilot to control VertiKUL [8]. The developed Pixhawk's firmware is based on ArduCopter source code and is called ArduVTOL [9].

3.1 Simulation

In order to present the attitude of VertiKUL, i.e. roll, pitch and yaw in both quadcopter mode as well as in plane mode, two reference frames are defined. A first frame $\mathcal{F}_{quad}$ (E_x^q, E_y^q, E_z^q) represents the UAV in quadcopter mode or hovering flight regime. A second frame $\mathcal{F}_{plane}$ (E_x^p, E_y^p, E_z^p) represents the UAV in plane mode or forward flight regime. As illustrated in figure 5, the origin of both frames coincides with the center of gravity of VertiKUL. The attitude expressed in $\mathcal{F}_{quad}$ is represented by the Euler angles roll ϕ_q, pitch θ_q and yaw ψ_q. Expressed in $\mathcal{F}_{plane}$ the attitude is represented by ϕ_p, θ_p and ψ_p.

Although Euler angles provide an intuitive way to represent VertiKUL's attitude, it suffers from singularities at a pitch angle of 90° or -90°. Because in forward flight attitude control is done close to such a singularity ($\theta_q = -90°$) the quaternion attitude representation is introduced. A quaternion is a set of four parameters and offers a singularity free mathematical representation of the attitude [10], [11]. A dynamical model of a virtual UAV is implemented in a Simulink simulation program to test several control strategies.

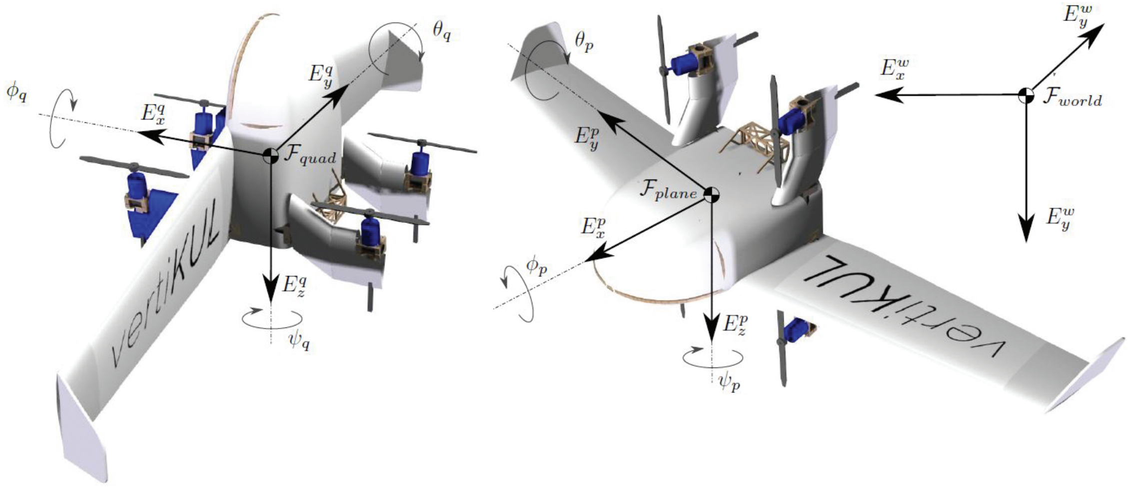


Figure 5: Quadcopter body frame Fquad , plane body frame Fplane and world frame Fworld .

3.2 Low-level Control Mode

In low-level control mode the transmitter's four channels correspond to desired collective thrust T, roll rate $\dot{\phi}_d$, pitch rate $\dot{\theta}_d$ and yaw rate $\dot{\psi}_d$. The low-level controller consists of three separate PID-controllers that translates desired angular rates into actuator moments that need to be invoked by the propellers through differential thrust. Only experienced UAV pilots can fly in this rate controlled low-level control mode.

3.3 Mid-level Control Mode

Because piloting VertiKUL in low-level mode requires a lot of practice, a mid-level control mode is developed such that any user without experience can pilot VertiKUL safely and intuitively. A distinction is made between two flight modes. Quadcopter mode corresponds to VertiKUL hovering like a conventional quadcopter and plane mode corresponds to the forward flight regime. In mid-level control mode, a smooth transition from hover to forward flight or back is commanded by a switch on the transmitter. During a transition to forward flight, the control system ignores pilot input and decreases pitch gradually until the stall speed has been exceeded and optimal angle of attack has been reached. Transition back to hover is performed faster because no forward speed needs to built up. Figure 6 shows prototype X3000 during forward flight in mid-level control mode.

Figure 6: X3000 prototype in mid-level control mode during forward flight.

In quadcopter mode, the transmitter's channels correspond to desired climb rate $\dot{h}_d$, roll angle ϕ_d, pitch angle θ_d and yaw rate $\dot{\psi}_d$. Desired altitude h_d and yaw angle ψ_d are obtained by integrating the desired climb rate and yaw rate input respectively. This way, drift on altitude can be compensated and heading can be maintained (heading-lock). The altitude controller converts an altitude error into a supplementary climb rate which is added to the user's commanded climb rate $\dot{h}_d$. This combined reference climb rate is converted into a reference climb acceleration which is regulated by a PI-controller that outputs a desired collective thrust. A feedforward term equal to VertiKUL's weight is added.

In plane mode, only two transmitter channels are used to command climb and turning rate. Desired yaw angle ψ_d and altitude h_d are again obtained by integrating the their corresponding rates. With both transmitter sticks centered, VertiKUL will maintain altitude and heading autonomously. Forward speed is not regulated. Two altitude control approaches are presented.

3.3.1 Thrust altitude control

A first approach uses the same controller as in quadcopter mode but with PI-gains optimized for forward flight. Also a feedforward term equal to steady-state thrust in forward flight or climb is added. This term is estimated from static equilibrium. Reference pitch, expressed in $\mathcal{F}_{plane}$, equals optimal angle of attack minus rigging angle and plus climb angle. The advantage of this strategy is that optimal angle of attack will always be maintained. This means that even with a different mass VertiKUL will fly most efficiently. A disadvantage is the possible oscillating collective thrust. Also, during descent the thrust can drop significantly which reduces the angular controllability by differential thrust. Furthermore, when the angle of attack becomes negative, more thrust will amplify an altitude error instead of reducing it.

3.3.2 Pitch altitude control

In a second approach a PI-controller regulates the combined reference climb rate and outputs a reference pitch. This pitch is supplemented with the same feedforward as in the first approach. Thrust is now solely determined by the feedforward added in the first approach. This strategy ensures a smooth collective thrust output. Another advantage is that when losing altitude the pitch will be commanded to rise and VertiKUL approaches a safe hover regime where collective thrust will be able to compensate gravity. One disadvantage is that optimal angle of attack is not always ensured, especially not with changing weight. However, weight can be estimated during hover flight to optimize the feedforward terms.

Whether in quadcopter mode or in plane mode, the desired roll, pitch and yaw angles ϕ_d, θ_d and ψ_d are regulated by a quaternion-based attitude controller which outputs reference angular rates expressed in $\mathcal{F}_{plane}$. Experimental evaluation of the mid-level control mode, using thrust altitude control, is presented in section 4.3.

4. REALISATION AND TESTING

The design of a non-conventional aircraft requires a trial-and-error approach where functionality increases with every iteration since it is not possible to base the design on already existing aircraft. Therefore, a series of six fully functional prototypes are built and tested, presented in figure 7. Based on the result of the numerical design optimisation approach described in section 2 the final VertiKUL prototype is built. Design parameters and performance are given in table 1.

4.1 Stability

For VertiKUL to be longitudinally stable, the center of gravity lies with a distance of 5% of the mean aerodynamic chord in front of the aerodynamic center. Figure 8 shows the internal component arrangement. Because VertiKUL is a tailless aircraft, a reflex profile (NACA23012) is used for low wing-moment.

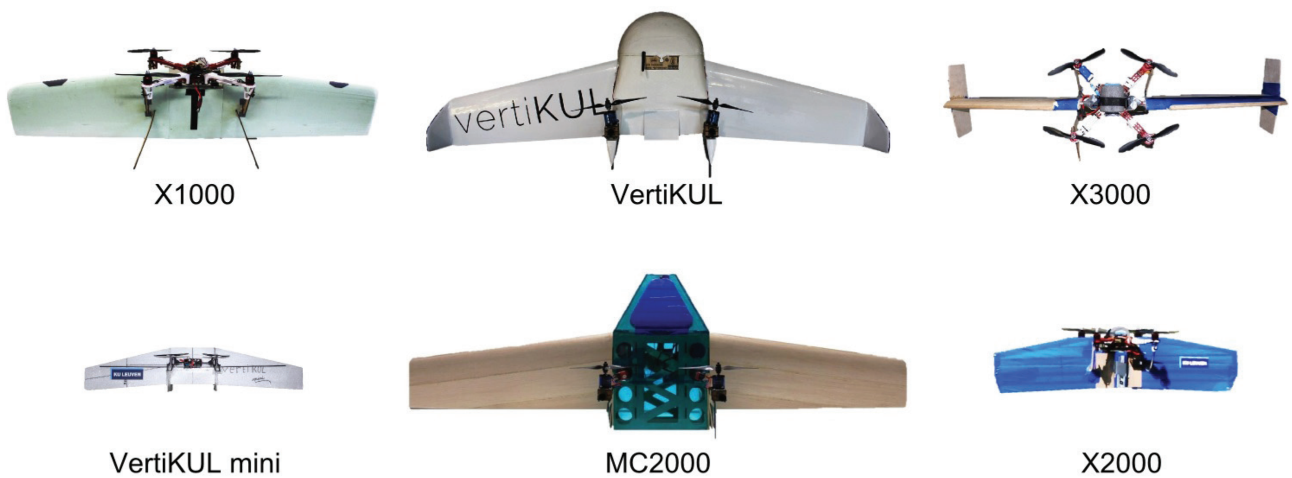


Figure 7: The different prototypes built during this thesis.

Winglets and wing sweep are added for directional stability. For structural reasons, the wing has no dihedral. However, winglet dihedral is used to accommodate for roll stability. As can be seen on figure 7, VertiKUL has inclined propellers. Thus sacrificing a small amount of thrust for better yaw control in quadcopter mode or roll control in plane mode.

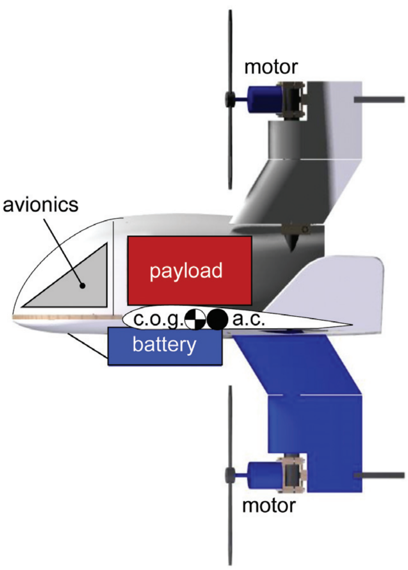


Figure 8: VertiKUL internal component arrangement.

4.2 General structure

Carbon composite tubes are used in the wing and fuselage for strength and stiffness. A laser- cut multiplex wooden structure is built around the carbon frame for payload and avionics support. The hull is made out of kraft paper reinforced polystyrene, cut with hot wire. A strong yet light sandwich structure from polystyrene and balsa wood is used for the wing and stabilisers. Figure 9 shows the exploded view of all structural components as well as the wing section.

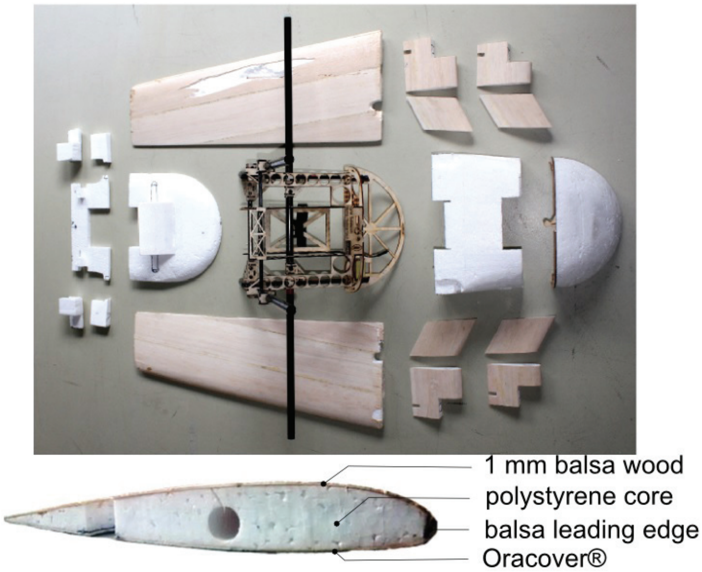


Figure 9: Exploded view and wing section.

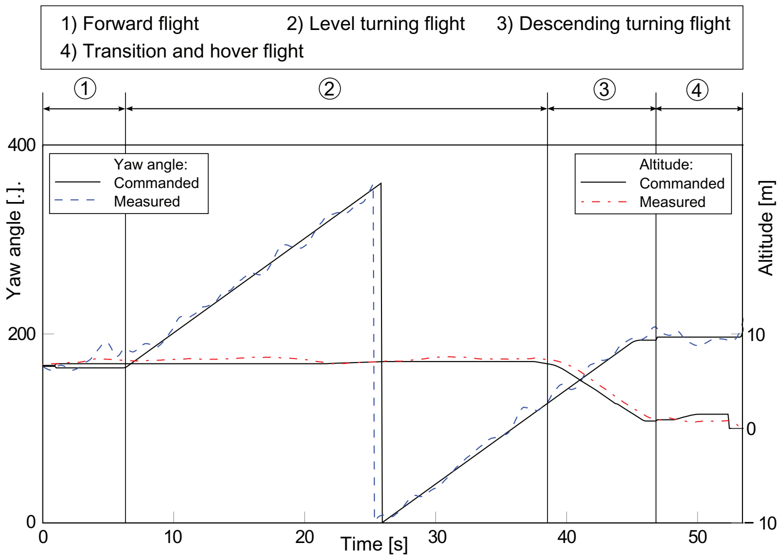


Figure 10: Reference- and measured yaw angle and altitude during the turning test flight.

4.3 Test flights

To validate the mid-level controller, ArduVTOL source code is tested and evaluated with prototypes X2000 and X3000.

4.3.1 Transition flight

Figure 11 shows altitude, GPS ground speed, reference- and actual pitch angle during test flight. While transitioning, pitch decreases gradually and forward speed increases, keeping constant altitude until a pitch set point is reached. During forward flight, climbing and descending flight altitude is regulated with thrust. While climbing with a commanded constant climb rate, the pitch angle increases. Transition to hover occurs fast with little overshoot in pitch angle.

4.3.2 Turning flight

Figure 12 shows the 3D circular flight path. A clockwise 360° turn is done in mid-level control mode. Altitude and turning rate stay constant through differential thrust regulation as can be seen on figure 10. Because no GPS signal was used for control, wind caused drifting. The end point of the circle shifted relative to the starting point in the direction of the wind.

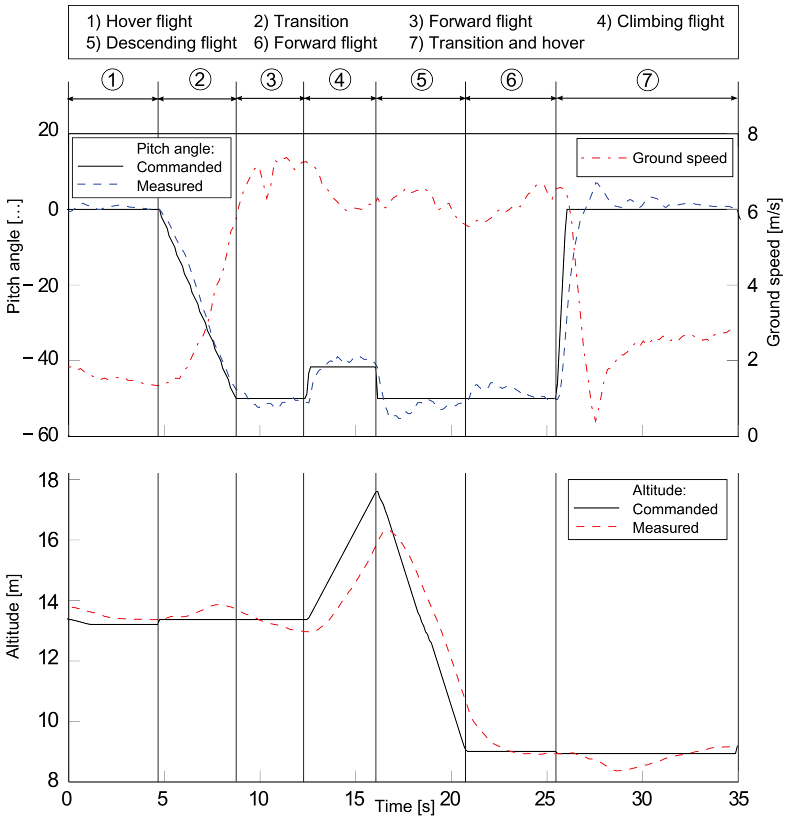


Figure 11: Altitude, GPS ground speed and pitch angle during transition test flight.

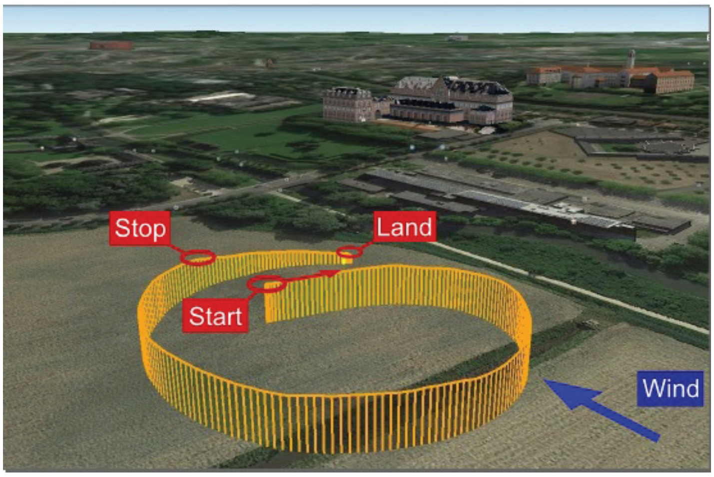
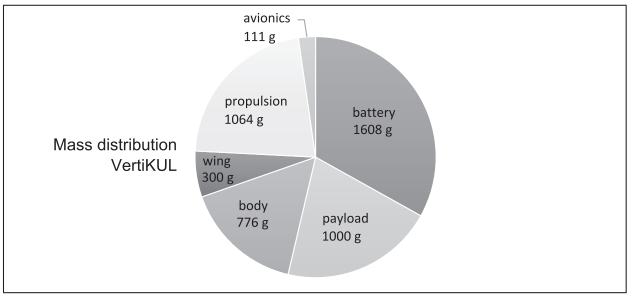


Figure 12: 3D circular flight path of the turning flight test.

Table 1: Design parameters and performance of VertiKUL.



	Parameter	Value
m_{tot}	MTOW	4.86 kg
m_{pld}	Payload	1 kg
R	Range	26 km
t_{tot}	Endurance	29 min
v_c	Cruise speed	15.5 m/s
v_{stall}	Stall speed	12.9 m/s
-	Wing airfoil	NACA23012
b	Wing span	1.60 m
S	Wing area	0.36 m^2
AR	Aspect ratio	7.11
ϵ	Cruise lift to drag ratio	7.5
C_L	Cruise lift coefficient	0.9
-	Thrust to weight ratio	2.17
-	Power to weight ratio	610 W/kg
-	Wing loading	13.5 kg/m^2
-	Propellers	APC *TE* 9x5″
-	Battery	6S2P 10,000 mA h
P_{max}	Max. single motor power	740 W
-	Motor kv-value	970 $min^{-1}\,V^{-1}$

5. CONCLUSIONS AND FUTURE WORK

This paper described design and control of VertiKUL. For initial sizing of VertiKUL, a numerical design approach optimising range was developed. In the dynamic model only the relevant aerodynamic effects were considered. However, estimating realistic aerodynamic coefficients proved to be difficult. Two control strategies for altitude regulation in mid-level control mode were proposed. By regulating the altitude with pitch angle, a smooth thrust output is ensured. Also, when losing altitude the pitch will be commanded to rise and VertiKUL approaches a safer hover regime. However, only test flights using the thrust strategy were conducted on the VertiKUL. Sufficient duration of transition appeared to be necessary to ensure stall speed is exceeded. Six fully functional prototypes were built and successful transitional flight was achieved. It was possible to perform transition and forward flight without using additional actuators and control surfaces. Intuitive mid-level control was demonstrated with autonomous transitional, turning, climbing and descending flight. In test flights, wind gusts turned out to have a big influence on hover stability. To overcome this problem, heading lock in quadcopter mode was relaxed and propellers were inclined for better yaw control.

In future work, the numerical design program will be expanded for more general configurations and with updated component models. CFD analysis and wind tunnel tests will be performed for a more precise estimation of the aerodynamic coefficients. To evaluate control strategies, test flights were performed at high angle of attack. However, to evaluate forward flight efficiency, tests at optimal angle of attack will follow. Also, pitch-regulated altitude control still needs to be evaluated in test flights. The stability advantage of a reflex profile should be re-evaluated because they suffer from low $C_{L,max}$ values. Lower stall speeds can be obtained with non-reflex profiles, making transition possible at lower speeds. To reduce wind disturbances in hover flight, wing area can be reduced when using part of the propeller thrust for lift during forward flight.

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